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# STATISTICAL TRENDS (OR LACK THEREOF) IN SOLAR PROTON EVENTS DURING THE LAST THREE SOLAR CYCLES

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## ABSTRACT

During the past three solar cycles, 218 "significant" solar proton events with a flux of over 10 particles (cm<sup>2</sup>-sec-ster)<sup>-1</sup> above 10 MeV have been detected at the earth. Other than a general increase in solar proton event occurrence with an increase in the sunspot cycle, no recognizable pattern could be identified between the number of solar proton events observed at the earth and the sunspot number.

## 1. INTRODUCTION

To study and analyze solar proton events over the past three solar cycles it is necessary to assemble a consistent list of solar proton events. Using a criterion that each event have a proton flux of over 10 particles (cm<sup>2</sup>-sec-ster)<sup>-1</sup> above 10 MeV (or equivalent riometer absorption) we have assembled a list of 218 solar proton events which have been recorded at the earth during the last three solar cycles. We have utilized this list to search for any recognizable pattern between the occurrence of solar proton events and the solar cycle.

## 2. DATA SOURCES

It is not possible to assemble a completely homogeneous list of solar proton events detected over the last three solar cycles, primarily because of different measurement techniques. However, we have assembled a list of solar proton events which is as homogeneous as possible using the criterion that each proton event must have a 10 MeV particle flux above 10 particles (cm<sup>2</sup>-sec-ster)<sup>-1</sup>. We selected this flux criteria as the flux capable of producing a definitive effect in the polar ionosphere, and identified these events as "significant" solar proton events.

Since the measurement techniques are not homogeneous over the entire three solar cycle period, the following data sources and criteria for event selection were as follows:

All polar riometer (or riometer equivalent) events with at least a 1.0 dB absorption were included unless satellite measurements indicated the > 10 MeV peak flux was lower than 10 particles (cm<sup>2</sup>-sec-ster)<sup>-1</sup>. (A practical "rule of thumb" useful for converting sunlit polar cap riometer absorption to proton flux is  $J = 10 A^2$ , where J is the flux of protons with energy > 10 MeV (in units of (cm<sup>2</sup>-sec-ster)<sup>-1</sup> and A is the 30 MHz polar cap riometer absorption.) The catalog by Svestka and Simon (1975) supplemented by Shea and Smart (1977) were our basic sources for the years 1955-1969. Our basic sources for 1970-1979 were Shea and Smart (1979) and the catalog by Akiniyan et al. (1982). The primary spacecraft data source for the period 1972-1986 was the data assembly of Krimigis and Armstrong (1988) who have processed the IMP 7 and 8 spacecraft data from 1972 to 1988 in order to generate a "uniform" assembly of proton flux data at standardized energy levels. In the later years when there were significant data gaps near the expected event maximum, satellite measurements from the synchronous orbiting GOES spacecraft were used (*Solar-Geophysical Data*, 1988).

When several sources overlapped in time, they were cross-checked for consistency. Questionable events were resolved in the following way. If satellites measured a minimum of at least 10 particles (cm<sup>2</sup>-sec-ster)<sup>-1</sup> above 10 MeV, the event was included. This was selected as the

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particle flux necessary to produce a 1.0 dB riometer absorption in the sunlit polar cap. If satellite measurements were not available, the polar cap riometer measurements were used.

Each separate solar particle injection was counted as an individual event even if the particle flux was enhanced from a previous increase. However, an additional particle increase related to a geomagnetic storm sudden commencement was not identified as a separate event. A detailed listing of these events is given by Shea and Smart (1990).

Using these various data sources and criteria, 218 discrete solar proton events were identified for the past three solar cycles (1955-1986). The number of events for each month of this 32-year period are listed in Table 1. Whenever an event started in one month and maximized the next month, the month of event onset was used for this table. From an inspection of the distribution of these 218 events, we find that significant solar proton events occur in episodes with a large variance in the distribution. There can be relatively long periods between significant events during the sunspot solar maximum (e.g. 1980), conversely, significant solar proton events, including even relativistic solar proton events, have occurred during solar minimum (e.g. 1976).

TABLE 1.  $E > 10$  MeV Solar Proton Events with Flux  $> 10$  (cm<sup>2</sup>-sec-ster)<sup>-1</sup>

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1955	1	.	.	.	.	.	.	.	.	.	.	.	1
1956	.	1	1	.	.	.	.	1	.	.	1	.	4
1957	1	.	.	2	1	1	2	4	3	1	1	.	16
1958	.	1	2	1	.	.	2	4	1	.	.	.	11
1959	.	1	.	.	1	1	3	1	.	.	.	.	7
1960	1	.	1	4	3	.	.	.	2	.	3	.	14
1961	.	.	.	.	.	.	4	.	3	.	1	.	8
1962	.	1	.	.	.	.	.	.	.	.	.	.	1
1963	.	1	.	.	.	.	.	.	2	.	.	.	3
1964	.	.	.	.	.	.	.	.	.	.	.	.	0
1965	.	1	.	.	.	.	.	.	.	.	.	.	1
1966	.	.	1	.	.	.	1	1	2	.	.	.	5
1967	1	1	1	.	2	1	.	.	.	.	.	1	7
1968	.	.	.	.	.	1	2	.	2	2	3	1	11
1969	.	4	1	1	1	1	.	.	2	.	1	.	11
1970	1	.	3	.	1	1	1	1	.	.	1	.	9
1971	1	.	.	1	1	.	.	.	1	.	.	.	4
1972	1	.	.	2	1	2	1	3	.	1	.	.	11
1973	.	.	.	1	.	.	.	.	1	.	.	.	2
1974	.	.	.	.	.	.	4	.	4	.	1	.	9
1975	.	.	.	.	.	.	.	1	.	.	.	.	1
1976	.	.	.	1	.	.	.	1	.	.	.	.	2
1977	.	.	.	.	.	.	.	.	3	.	1	.	4
1978	.	1	.	6	2	1	1	.	1	1	2	.	15
1979	.	1	.	2	.	1	1	2	1	.	1	.	9
1980	.	1	.	.	.	.	1	.	.	1	.	.	3
1981	.	.	1	5	3	.	2	1	.	2	.	1	15
1982	1	1	1	.	.	2	3	.	1	.	3	5	17
1983	.	1	.	.	.	1	.	.	.	.	.	.	2
1984	.	2	2	1	2	.	.	.	.	.	.	.	7
1985	1	.	.	1	.	.	1	.	.	.	.	.	3
1986	.	3	1	.	1	.	.	.	.	.	.	.	5
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
	9	21	15	28	19	13	29	20	29	8	19	8	218

### 3. THE QUESTION OF SEASONAL TRENDS

In the identification of proton events from an interpretation of ionospheric data, two pronounced seasonal trends have been identified. The riometer is most sensitive to the sunlit polar ionosphere, and since most polar ionosphere observing sites are in the northern hemisphere (particularly during the 19th solar cycle), there is a distinct northern hemisphere bias in the ionospheric data set with more events reported in the northern hemisphere summer than the northern hemisphere winter. The ionosphere also has a strong response to geomagnetic activity which has a statistically significant peak during the equinox (Allen, 1982). As shown in Figure 1, these two effects combine to give a very non-uniform temporal distribution of the data assembly which might be interpreted as a seasonal effect unless one were aware of the detector responses.

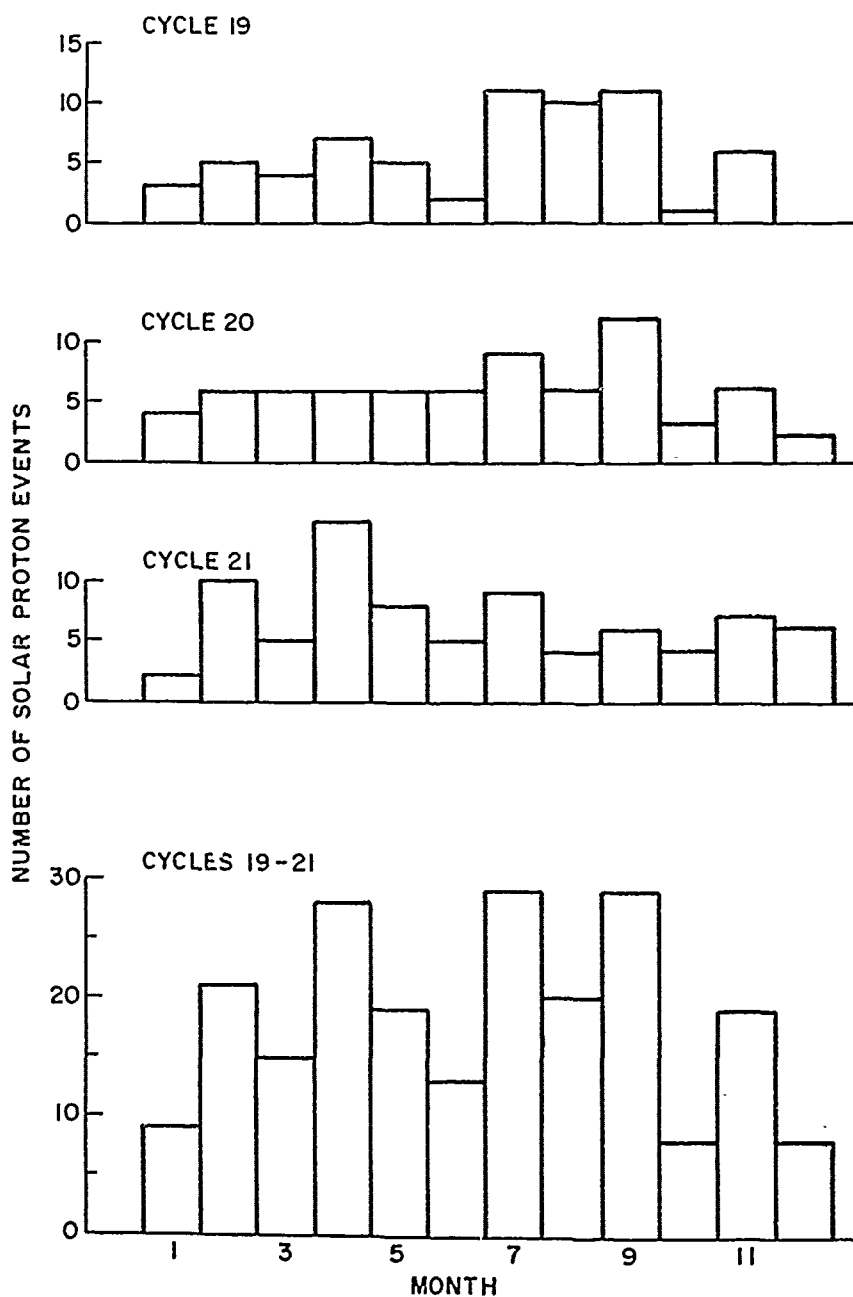


Figure 1. Non-uniform temporal distribution of the proton event data assembly for three solar cycles.

#### 4. SOLAR PROTON EVENTS FOR SUNSPOT CYCLES 19-21

Since most major flares and proton events occur in conjunction with sunspot activity, we used the monthly mean sunspot number as our major ordering parameter (McKinnon, 1987), however, we used the smoothed sunspot number to define the length of each cycle since the monthly mean numbers have a wide variance. We then separated the events in our list into individual solar cycles with the start of each cycle being the first month after the minimum defined by the smoothed sunspot number.

The top portion of Figure 2 shows the number of solar proton events that occurred each 12-month period after sunspot minimum for the past three solar cycles; the 12-month mean sunspot number for the same time periods is also shown in the bottom of the Figure. The shape of the three histograms in the top part of Figure 2 are all different, and beyond the obvious fact that there are more solar proton events during solar activity maximum than at solar minimum, there does not appear to be any repeatable solar cycle pattern.

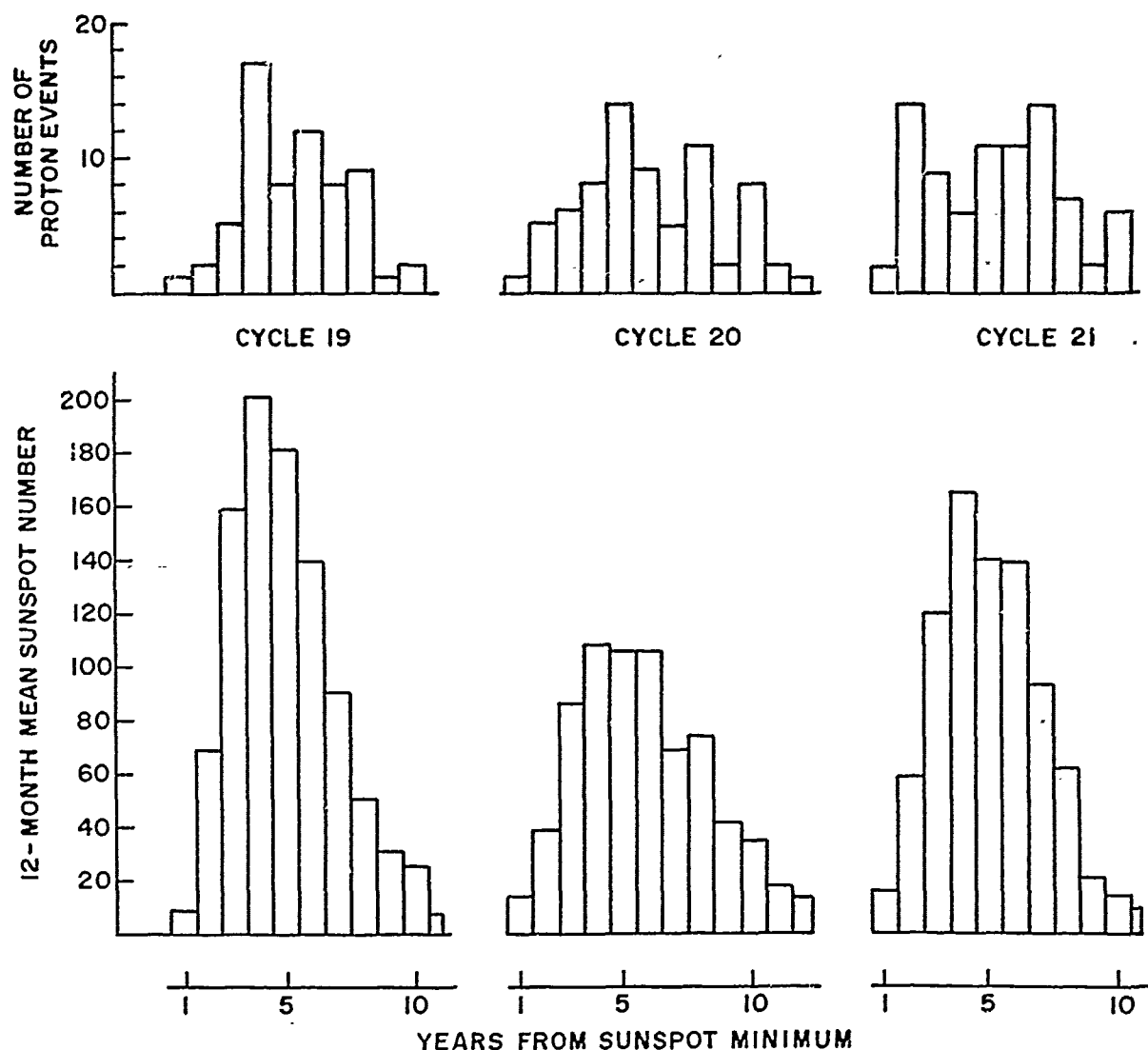


Figure 2. The number of significant discrete solar proton events for each 12-month period after solar minimum (top) and the 12-month mean sunspot number for the corresponding period (bottom) for the past three solar cycles.

Using solar minimum as our fiducial mark, we summed the number of solar proton events for successive 12-month periods after statistical sunspot minimum for the past three solar cycles. From these results we find that the majority of solar proton events for the past three solar cycles occurred from the second through eighth years after sunspot minimum as illustrated in Figure 3.

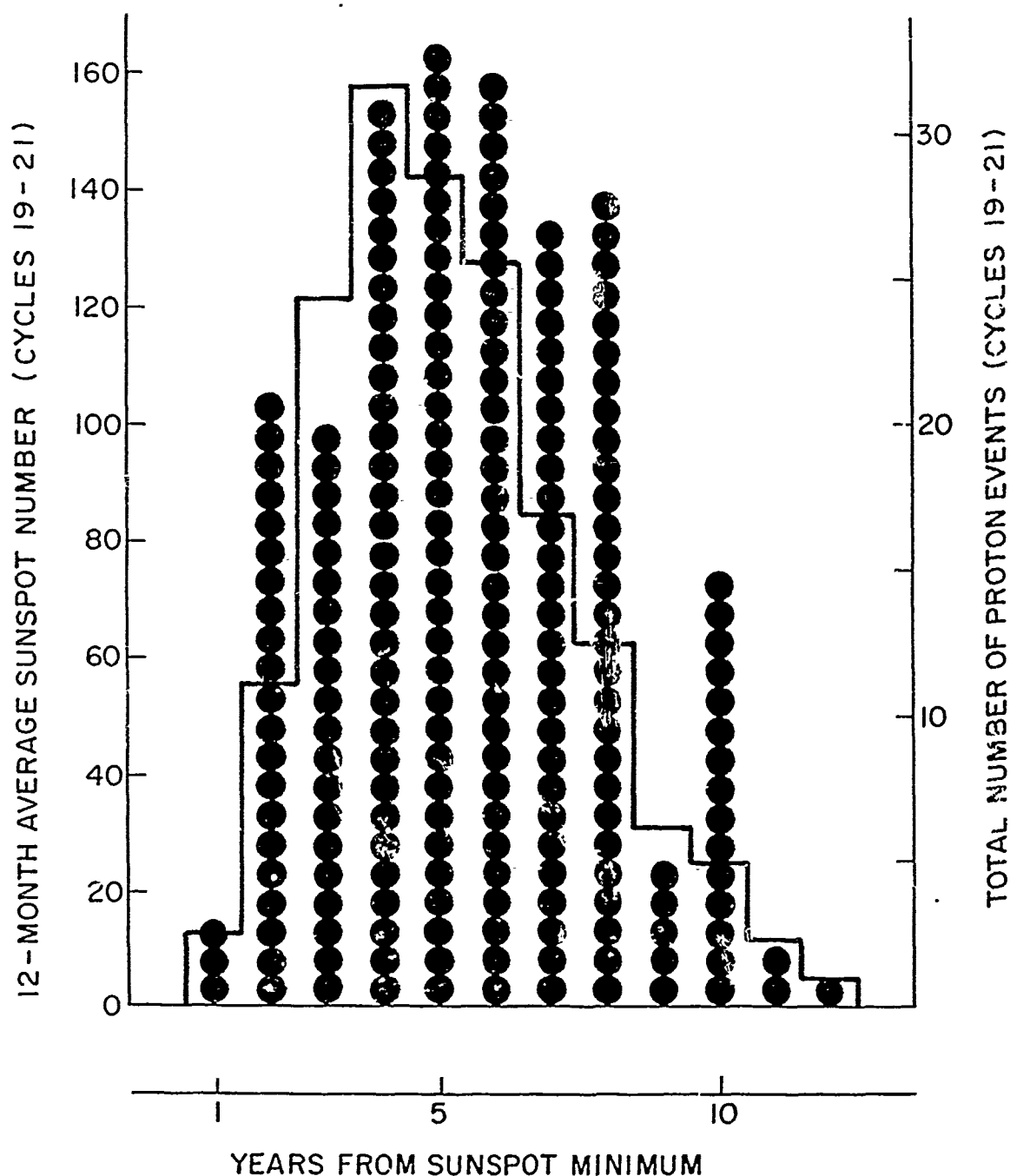


Figure 3. Summation of significant discrete solar proton events for cycles 19-21 (solid circles) and the corresponding 12-month average sunspot number (histogram). The data are organized in 12-month periods beginning with the month after sunspot minimum as defined by the statistically smoothed sunspot number.

## 5. EPISODES OF ACTIVITY

In compiling the list of significant solar proton events we identified each event with a solar flare on the sun, in most cases using the identification given in each of the data sources. We then calculated the number of discrete solar proton producing regions associated with proton events detected at the earth for each of the last three solar cycles (i.e. multiple events from the same region contributed to only one episode and was only counted once). In the case where multiple flares on the sun in different regions may have contributed to the aggregate particle event observed at the earth, we selected the most likely flare as the source of the proton event. From this study we find that for each of the last three solar cycles at least 22% of the significant solar proton events observed at the earth are from solar regions that produce at least two or more discrete proton events.

## 6. SUMMARY

In this examination of significant solar particle events that have been detected at the earth during the past three solar cycles, we did not find any recognizable pattern between the occurrence of solar proton events and the individual solar cycles as defined by the sunspot number. In summing the results for all three cycles we found that the majority of solar proton events occurred from the second through the eighth years after sunspot minimum. We also found that proton events often occur in episodes of activity with 22% of the significant solar proton events observed at the earth emanating from solar regions that produce at least two or more discrete proton events.

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